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THESIS

AN EXPERIMENTAL INVESTIGATION OF VARIOUS METALLIC/POLYMER FUELS IN A TWO-DIMENSIONAL SOLID FUEL RAMJET

by

Charles Kenneth Scott II

March 1986

Thesis Advisor: D. W. Netzer

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below approximately 40 psia. Low air mass fluxes generally resulted in larger metallic surface agglomerations, larger particles in the gas phase and more dominate shedding of surface layers.

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An Experimental Investigation of Various Metallic/Polymer Fuels in a Two-Dimensional Solid Fuel Ramjet

by

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Lieutenant, United States Navy
B.S., SUNY at Brockport, 1977

Submitted in partial fulfillment of the
requirements for the degree of

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ABSTRACT

An experimental investigation was conducted of highly metallized (approximately 70% by weight) solid fuels burned in a two-dimensional solid fuel ramjet (SFRJ). High speed motion pictures were taken of the combustion process through viewing windows located at two locations along the fuel slab length. Films revealed various ejection events ranging from small particle ejections to large flakes of burning and non-burning material leaving the surface. Nine different fuels were tested at air mass fluxes of 0.2 and 0.5 pounds mass per inch squared per second and pressures ranging from 35 to 200 psia. There was evidence that both minor binder ingredient changes (polymer and curative) and the inclusion of magnesium resulted in larger required inlet step heights to sustain combustion. Most of the metallized fuels did not burn well at pressures below approximately 40 psia. Low air mass fluxes generally resulted in larger metallic surface agglomerations, larger particles in the gas phase and more dominate shedding of surface layers.

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I. INTRODUCTION

The air breathing solid fuel ramjet motor is a proposed power plant for the next generation of tactical missiles. It's major advantages over the presently employed solid propellant rockets are increased range and power-to-target. Continuous power during the terminal phase would greatly increase the probability of hit against an evasive target, thereby increasing the effectiveness and lethality of the damage mechanism.

Various fuels have been proposed for the solid fuel ramjet. Hydrocarbon fuels such as HTPB and polymethylmetacrylate (PMM-Plexiglas) have been studied extensively. Some metals such as boron, boron compounds, aluminum, lithium, magnesium, and titanium possess very high energy densities. Boron for example, exhibits 30% more energy per unit mass and 300% more energy per unit volume than typical hydrocarbon fuels [Ref. 1]. High energy density metals are excellent fuel ingredient candidates and are under investigation. Typically, powdered metals are suspended in a hydrocarbon matrix to enhance combustion efficiency and to improve material properties. Metal concentrations and particle sizes can be varied over significant ranges. The combustion process for hydrocarbon fuels is reasonably well understood and semi-empirical fuel regression rate and combustion efficiency correlations have been found to be quite reliable. However, little is known about the combustion process of highly metallized fuels. Previous studies [Ref. 1] of fuels containing magnesium as one metal ingredient have observed large agglomerates of molten metal which grow in size on the surface of the fuel grain prior to their ejection into the core stream. Particle and agglomerate ejections were postulated to be caused by either a pressure increase within the agglomerate or gas flow from the decomposition of the hydrocarbon matrix. Agglomerates may grow in size and become unstable in the turbulent boundary layer. Upper surfaces of the moltent agglomerate may then be shed due to exposure to higher flow velocities.

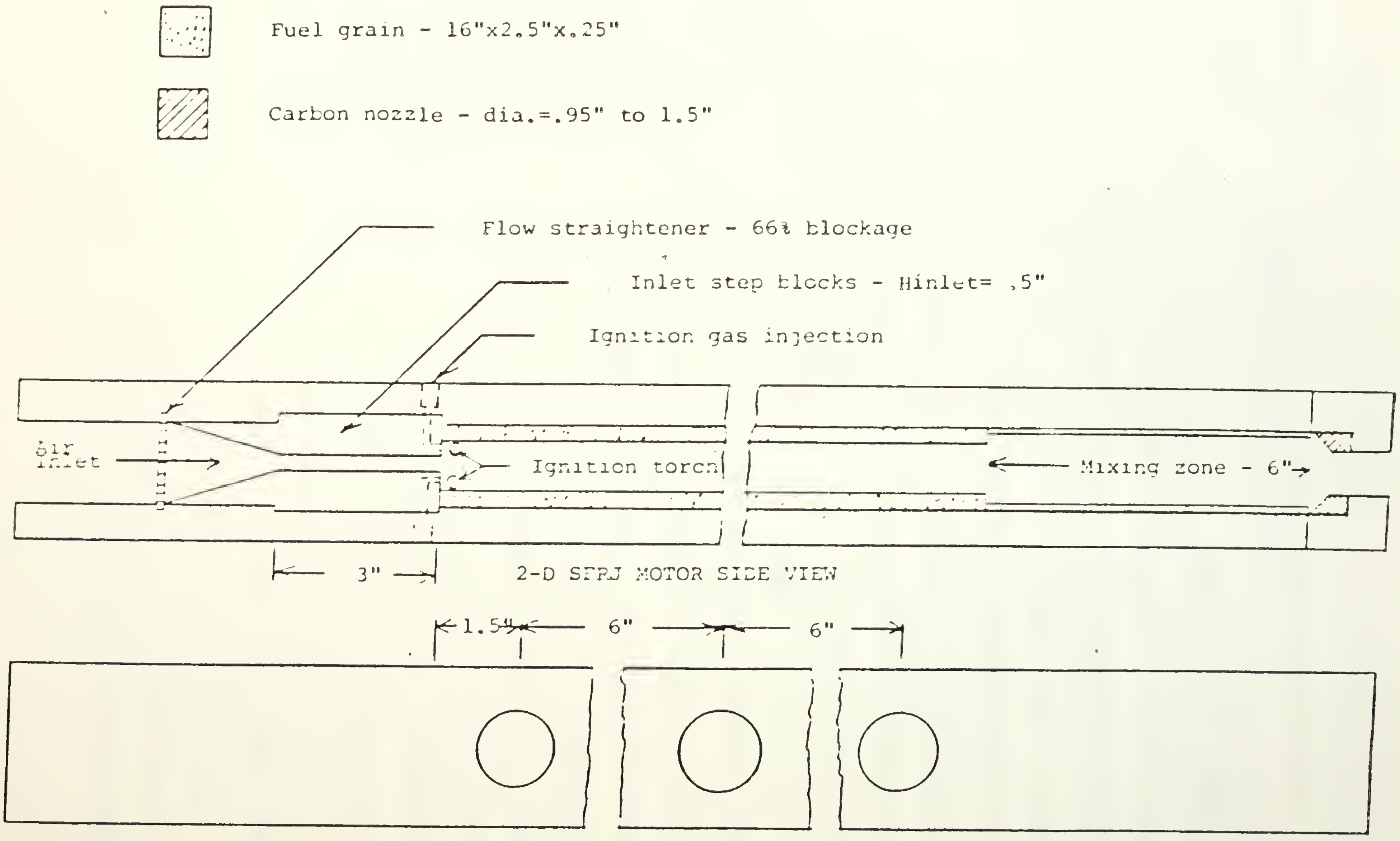
The initial work reported in [Ref. 1] was limited in scope, concentrating on only one or two fuel compositions. No information on the effects of metallic fuel ingredients on the surface and/or gas phase combustion processes have been reported.

In order to describe the combustion process of highly metallized fuels, more information must be gathered on metal particle size, the ejection event, agglomerate sizes, particle trajectories, ignition time, and ignition location. These parameters will vary from one fuel to the next as metallic composition, particle size, catalyst, and binder compositions are varied.

This investigation had several objectives. It was necessary to improve the two-dimensional motor design used in [Ref. 1] to eliminate the need for auxiliary gaseous fuel to maintain combustion and to provide more observation points for the high speed motion pictures. It was also necessary to study the combustion process under the higher air mass flux environments typical for tactical missiles. Finally, a wider variety of fuel ingredients needed to be studied in order to expand the knowledge of the surface and gas-phase combustion phenomena to the point where models can begin to be developed.

II. DESCRIPTION OF APPARATUS

A 3000 psi air supply with a vitiated (methane with oxygen make-up) air heater provided air to the solid fuel ramjet test stand at the proper temperature and pressure to simulate actual flight conditions. Air flow rate was regulated by means of a sonic choke. The two dimensional motor had four basic sections (see Figures 2.1 and 2.2): (1) the head end with air inlet and rearward facing step, (2) the main combustion section where the fuel slabs were placed on opposite walls (top and bottom) and the camera viewing windows were positioned in the side wall, (3) the aft mixing chamber (downstream of the fuel) where the reaction between fuel and air is enhanced due to better mixing and/or increased residence time, and (4) the exit nozzle. The motor chamber was 2.5 inches wide. The head end had a flow straightener followed by inlet step blocks which reduced the flow height (usually to 0.5 inches). The motor height (distance between opposing fuel slabs) was 1.0 inch. The inlet step height was usually 0.25 inches. Fuel slabs were 2.5 inches wide, 0.25 inches thick, and 16 inches long. Three Plexiglas viewing windows were positioned at, (1) the reattachment point, (2) mid-chamber and (3) just prior to the mixing chamber where


Fuel grain - 16"x2.5"x.25"
Carbon nozzle - dia.=.95" to 1.5"
Flow straightener - 66% blockage
Inlet step blocks - Hinlet= .5"
Ignition gas injection
air inlet
Ignition torch
Mixing zone - 6"
3"
2-D SFRJ MOTOR SIDE VIEW
1.5"
6"
6"

Window locations
Front window 1.5" from inlet step

Figure 2.1 Schematic of the SFRJ Motor

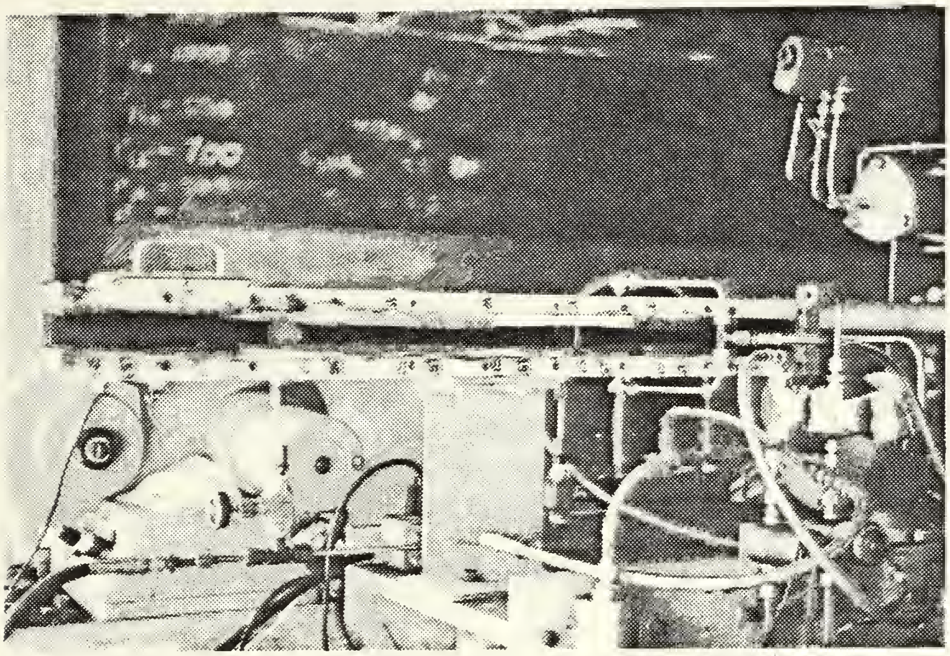


Figure 2.2 SFRJ Motor Side View with Left Side Removed

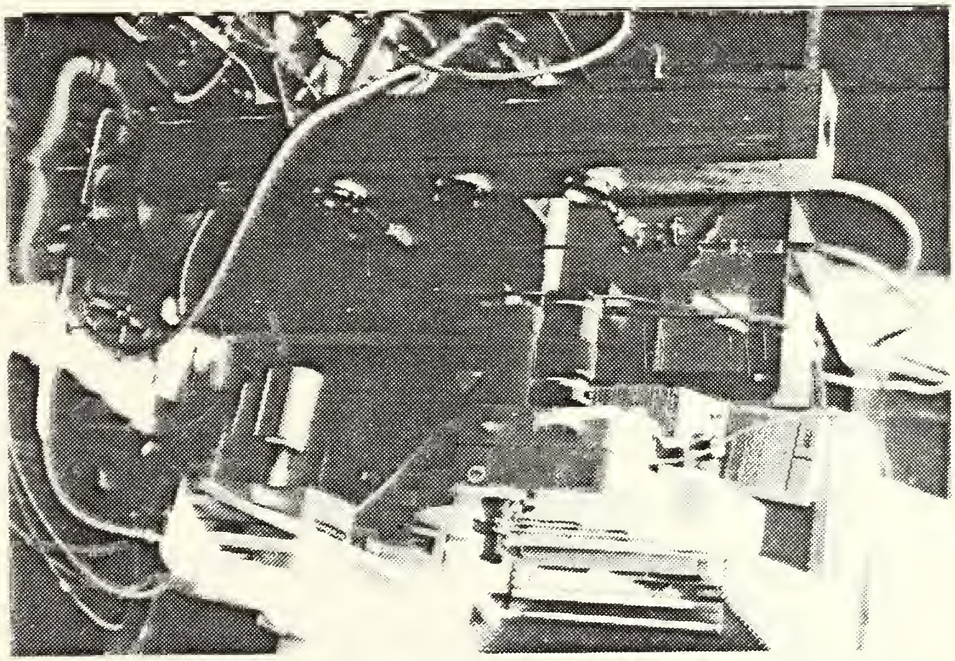


Figure 2.3 SFRJ Motor Top View Showing Camera Orientation

the boundary layer should be fully developed. Windows one and three could be viewed simultaneously with two adjacent Hycam cameras (see Figure 2.3). Air injected through a sintered bronze ring was used to purge the windows. Nitrogen was initially used, but it was found to quench the combustion process. Also, ceramic and metal shields were used to partially cover the window ports to prevent the windows from fowling or burning. The aft mixing chamber was 6 inches long. The nozzle block fit to the back end of the motor. Various diameter nozzles could be inserted into the nozzle block. Exit nozzle diameter was used to adjust the combustion chamber pressure for any specified air flow rate.

The motor was ignited by means of two ethylene-oxygen torches. The torches were directed into the recirculation zones in the across-motor direction. Ethylene was also injected into the recirculation zones at the inlet steps to aid the ignition process. Once the motor was ignited, the torches and ethylene were shut off and the SFRJ fuel was allowed to burn unaided.

The combustion process was observed by means of two Hycam (Red Lakes Labs) high speed motion picture cameras. These cameras are capable of framing rates to 12,000 pictures per second (pps). For this study 6000 pps were used. A Hewlett-Packard data acquisition system was used to acquire all pressures and temperatures. This data was further reduced by a Hewlett-Packard PC and a computer program developed previously. The program outputs were time, air flow rate, heater fuel flow rate, heater oxygen flow rate, ignition fuel flow rate, motor inlet air temperature, and combustion pressure as function of time. The system was also capable of measuring thrust, but this was not used in the present study. Analog data were also recorded through the use of a Visicorder. Combustion chamber pressure, ignition fuel pressure, heater fuel pressure, heater oxygen pressure, and air sonic choke pressure were recorded.

III. EXPERIMENTAL METHOD

Air was heated to approximately 1100 degrees Rankine and delivered to the motor at a pressure and flow rate to simulate typical flight conditions proposed for this type motor. Three combustor test conditions were explored: (1) an air mass flux of 0.2 lbm per second per square inch with a chamber pressure of approximately 50 psi, (2) a mass flux of 0.5 lbm per second per square inch with a chamber pressure of approximately 70 psi and (3) a mass flux of 0.5 lbm per second per square inch with a chamber pressure of approximately 180 psi. These air mass fluxes corresponded to air mass flow rates of .5 and 1.25 lbm per second.

Fuels containing high concentrations of powdered metal (approximately 70% by weight) suspended in a hydrocarbon polymer binder (typically HTPB) were burned in the motor. Metallic ingredients such as titanium, boron, boron carbide, lithium floride, magnesium, and aluminum were varied in their concentrations and particle sizes. Fuel samples were provided by the Naval Weapons Center, Chemical Systems Division of United Technologies and the Atlantic Research Corporation.

The motion pictures were analyzed using a stop action projector. Surface and adjacent gas flow combustion phenomena were observed. Ejection phenomena were analyzed for trajectories and velocity of ejection. Videotapes were also made of the exhaust plumes in order to determine if the different fuels ejected different amounts of unburned material.

Slabs of fuel containing metal were placed in front of the viewing windows on the bottom of the motor. Except for one test, the upper fuel slab was HTPB or Zecorez. It would be preferable to put metallized fuel on both the upper and lower surfaces of the combustion chamber, but the high cost and limited availability of the metallized fuel slabs usually prohibited this.

IV. RESULTS AND DISCUSSION

A. MOTOR OPERATION

Initially, the two-dimensional motor was designed with one ethylene ignition torch which was directed into the recirculation zone just above the bottom fuel grain. It was perpendicular to the gas flow and could impinge on the window located in the opposite wall. Two problems arose from this design. First, the motor tended to ignite only on the lower fuel grain at lower pressures (less than 100 psia). Second, the torch tended to cause the adjacent window to fowl or burn during the ignition process. These problems were rectified through the use of a second torch and angling the torches 20 degrees upstream so they impinged

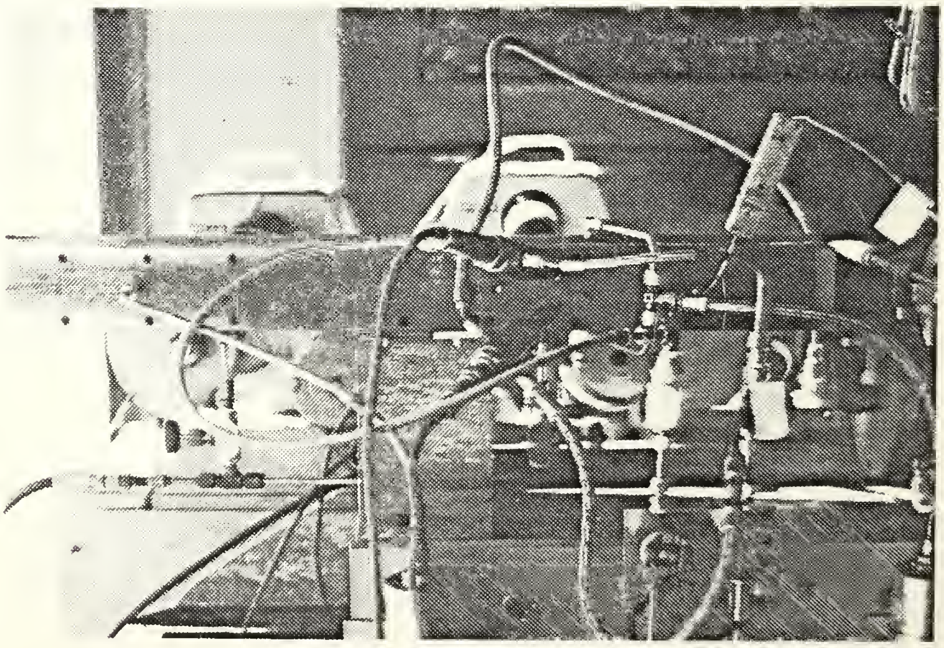


Figure 4.1 Torch Configuration

on the steel inlet step instead of the viewing window (see Figure 4.1). This design reduced the time required for ignition from as much as 10 seconds down to 1.5 seconds. This greatly improved the cleanliness of the viewing windows as they had to endure the combustion environment and/or igniter for substantially less time.

The windows proved difficult to keep clean enough to allow motion pictures to be taken, and they went through several design iterations. Initially, 1.5 inch diameter Plexiglas windows alone were used. Nitrogen was injected through sintered bronze bushings to keep the combustion process away from the windows. This design proved unacceptable for the large windows. It became apparent that the combustion process was being quenched in the critical recirculation zone because the motor would sustain combustion with a metal plug in the recirculation zone window port. This indicated that heat loss to the window cavity and/or the nitrogen purge were quenching the combustion process. The solution was to make a 1.5 inch diameter steel plug with a 0.5 inch hole drilled in it to allow viewing of the metallized fuel through a reduced area. Compressed air was substituted for nitrogen as the purge gas. This design cut down on the heat loss and proved quite acceptable from the stand point of ignitability and cleanliness of the viewing windows.

Motor inlet air temperatures ranged between 1030 and 1260 degrees Rankine. Typically, the increase in air temperature during a 4 second run was 20 degrees Rankine. The initial temperature and the temperature rise varied primarily with air mass flux, with larger variations occurring at lower flow rates. Motor chamber pressures ranged between 35 psia and 200 psia. Pressure was controlled by varying the exit throat diameter.

B. FUELS

1. Overview of the Combustion Characteristics

Fuels were provided by the Naval Weapons Center (NWC), Chemical Systems Division of United Technologies (CSD) and the Atlantic Research Corporation (ARC). Initial, motor check-out was conducted using NWC HTPB at high pressure (approximately 180 psia). The supply of this fuel type was exhausted and CSD Zecorez was then used to determine test conditions for the metallized fuels to follow. The proper air flow rates, chamber pressures, temperatures, ignition procedures and purge rates were finalized used CSD Zecorez.

CSD metallized fuels were provided in the form of 0.25 inch thick slabs, 3 inches by 5 inches. Not enough fuel was provided to fill the top and bottom of the motor, so Zecorez was used on top. On the bottom, metallized fuel strips 1.5 inches wide and 16 inches long were laid down in front of the windows. Zecorez strips 1.0 inch by 16 inches were laid down next to the metallized fuel to fill the bottom of the motor. The CSD fuels generally burned well at the established test conditions. A few of the fuels demonstrated a low pressure ignitability limit, below 40 - 50 psia. Most burned well when the chamber pressure was raised slightly by installing a smaller diameter exhaust nozzle. The step height to motor height ratio (H/D) for all CSD fuel tests was 0.25.

The ARC Boron/Magnesium fuel burned well at high pressure (193 psia). It would not sustain combustion at any pressures ranging from 55 - 85 psia. ARC provided enough fuel to cover the entire lower surface. Zecorez was used on the top surface of the motor. One of the low pressure tests used a fuel configuration similar to the CSD tests with a one inch wide strip of Zecorez on the bottom and a 1.5 inch wide strip of metallized fuel. This test also failed to sustain combustion at 52 psia. The ARC Boron/Teflon fuel burned well at both high pressure and low pressure. H/D for the ARC tests was also 0.25.

NWC provided fuel in the form of 0.25 inch thick slabs, 3 inches by 17 inches. This made it possible to cover the entire bottom of the motor with a continuous fuel slab. The normal configuration was to install Zecorez on the top of the motor, although one test was conducted with metallized fuel on both the top and bottom fuel surfaces.

The continuous fuel slabs are ideal in that there are no surface irregularities to interfere with the flow. This minimizes near-wall disturbances and provides for more stable boundary layer flow. Unfortunately, the NWC fuels failed to burn at either high or low pressures with H/D equal to .25. Also, the CSD fuel configuration was attempted with negative results. The H/D was increased to 0.325, resulting in good burns of the NWC fuels tested. Time did not permit a complete test series of the NWC fuels. The step height sensitivity of certain fuels should be investigated in future studies.

Table 4.1 summarizes the ignition characteristics of the fuels tested.

TABLE 4.1

SUMMARY OF FUEL IGNITABILITY CHARACTERISTICS

Fuel	Comments
CSD Zecorez	Burned well at all conditions
CSD Ti/2B	Burned well at all conditions
CSD Ti/2B/LiF/Mg	Poor combustion with $P<50$ psia Burned well above 70 psia
CSD Ti/2B/AlB_{12}/LiF/Mg	Poor combustion with $P<50$ psia Burned well above 70 psia
CSD Ti/2B/Teflon	Poor combustion with $P<40$ psia Burned well with $P>50$ psia
ARC B/Mg	Would not burn with pressure between 55 and 85 psia or with Zecorez strip Burned well at 193 psia

TABLE 4.1 (contd)

SUMMARY OF FUEL IGNITABILITY CHARACTERISTICS

Fuel	Comments
ARC B/Teflon	Good combustion at all pressures
NWC HTPB	Would not burn with H/D=.25 except at high pressure
NWC B_4C/Mg-Equal %	Would not burn with H/D=.25 Good combustion with H/D=.325
NWC B_4C/Mg-5%/Higher B_4C 5% Lower Mg	Good combustion with H/D=.325
NWC B_4C/Mg-20% Higher B_4C 25% Lower Mg	No burn with H/D=.25 at high pressure

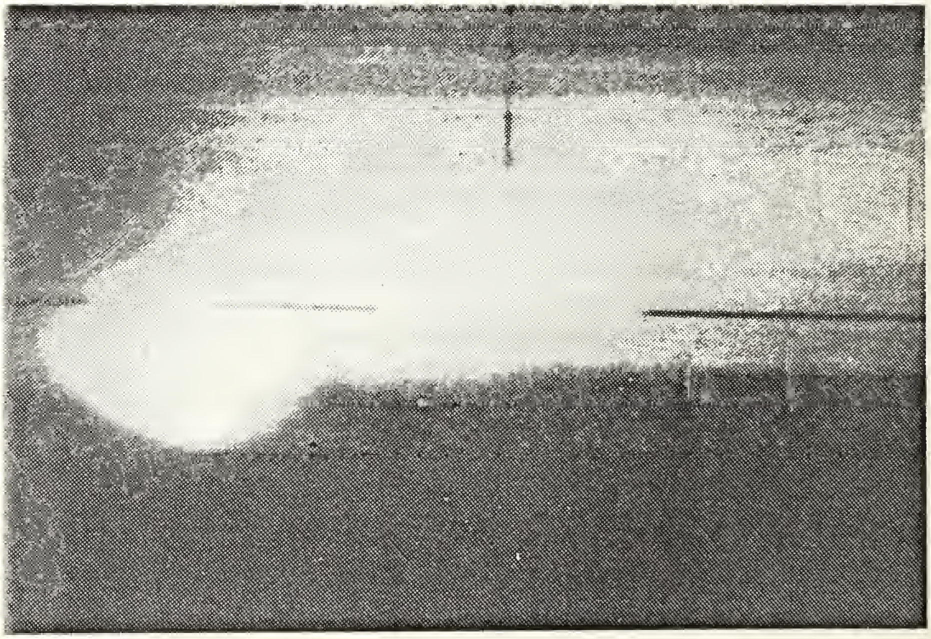
One possibility for the differences in ignitability of the various fuels is the curative agent used in the HTPB which forms the matrix of the metallized fuels. Three different curative agents were used by the three fuel suppliers (IPDI, DDI and TDI). Also, two slightly different uncured polymers were used, R45M and R45HT. Shore hardness tests were conducted on all fuel samples. With the exception of ARC B/Teflon, the higher the Shore hardness the poorer the ignitability (sustained combustion). Shore hardness can be influenced by the degree to which the HTPB is cross-linked (which is a function of the curative) and the metallic constituents. The effects of differences in the HTPB and the curatives on ignitability should be further investigated in future studies.

2. Burning Characteristics from Motion Picture Studies

General comments are contained in Table A2 of Appendix A for all successful films taken.

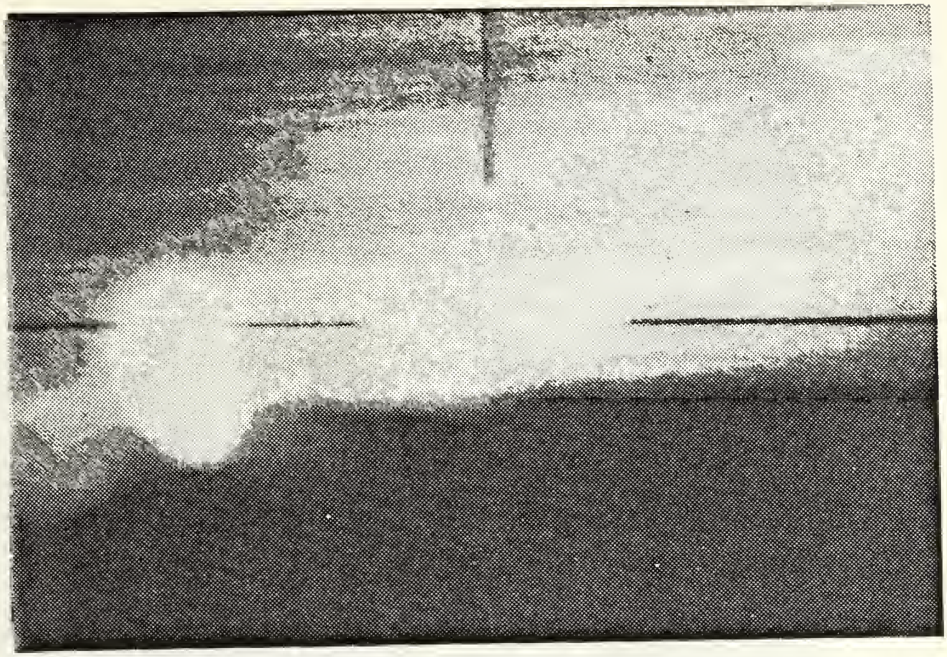
a. Ti/2B (Large Particle Sizes) at Low G in the Boundary Layer Region

A typical surface sequence is shown in Figure 4.2. It shows a large surface agglomerate rolling off the surface and entering the core flow. In the last frame it is contrasted with a particle of similar size at the velocity of the core flow. Also seen are numerous small particles in the gas phase. Their high velocity is evident by the streaking on the film. The scale of the photographs is 0.625 inches wide by 0.5 inches high. Each frame represents approximately

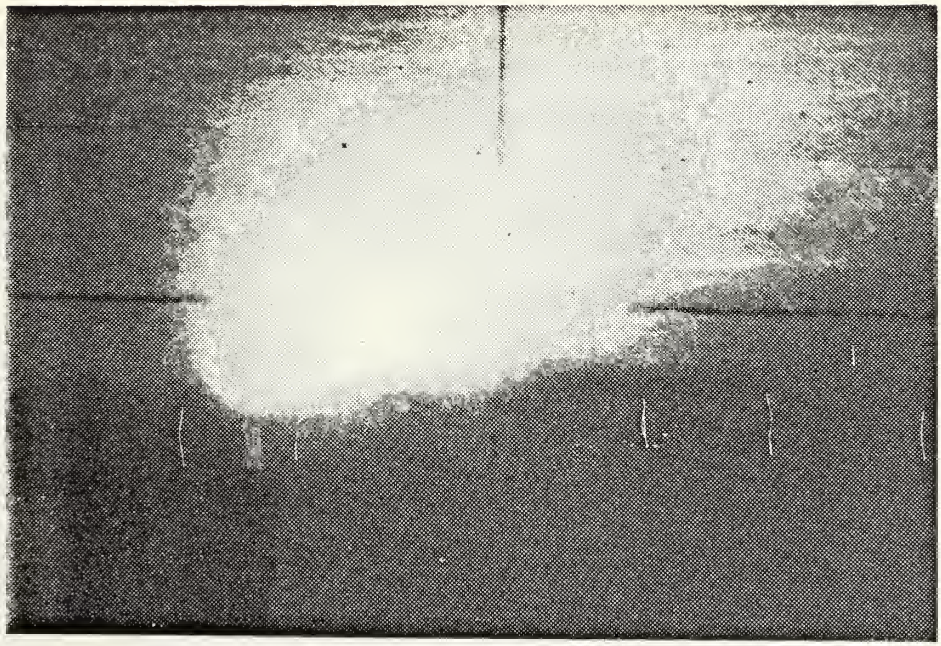


a. First in Sequence of Five

Figure 4.2 Ti/2B at Low G in the Boundary Layer (Scale: 1"=3.175mm, Time Between Frames=1/3000s)

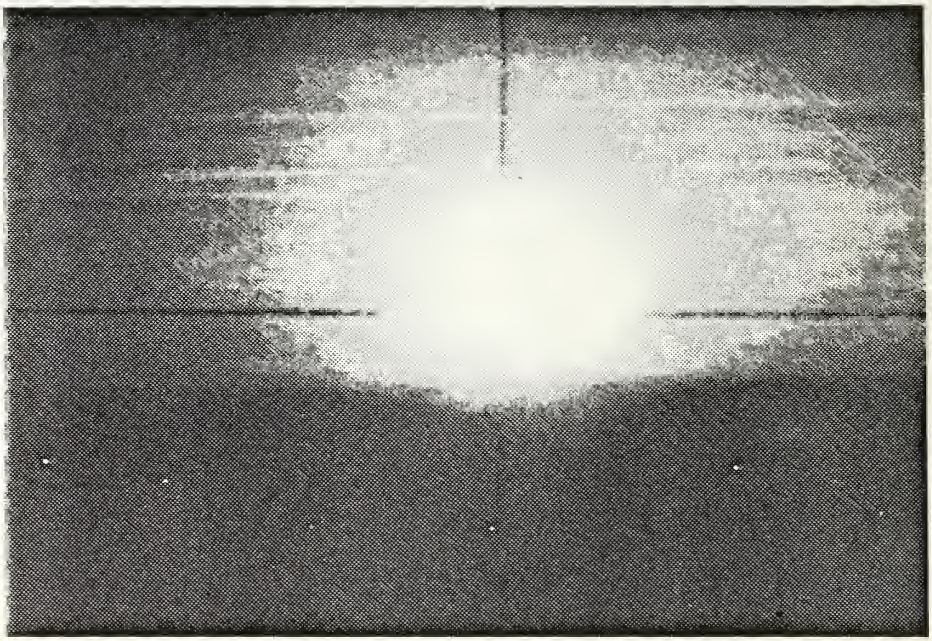


b. Second in Sequence of Five

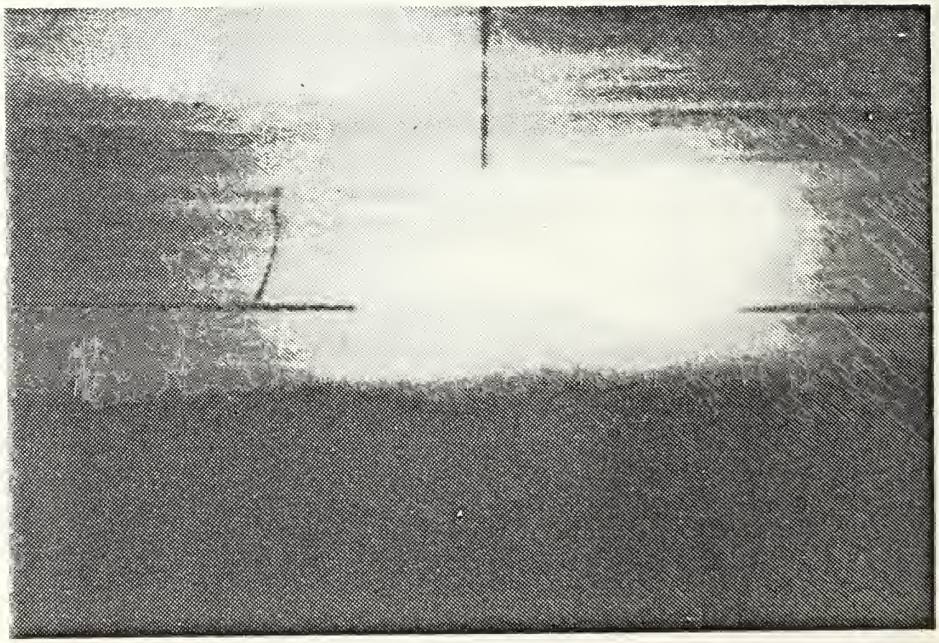


c. Third in Sequence of Five

Figure 4.2 Ti/2B at Low G in the Boundary Layer (Scale: 1"=3.175mm, Time Between Frames=1/3000s) (contd)



d. Fourth in Sequence of Five

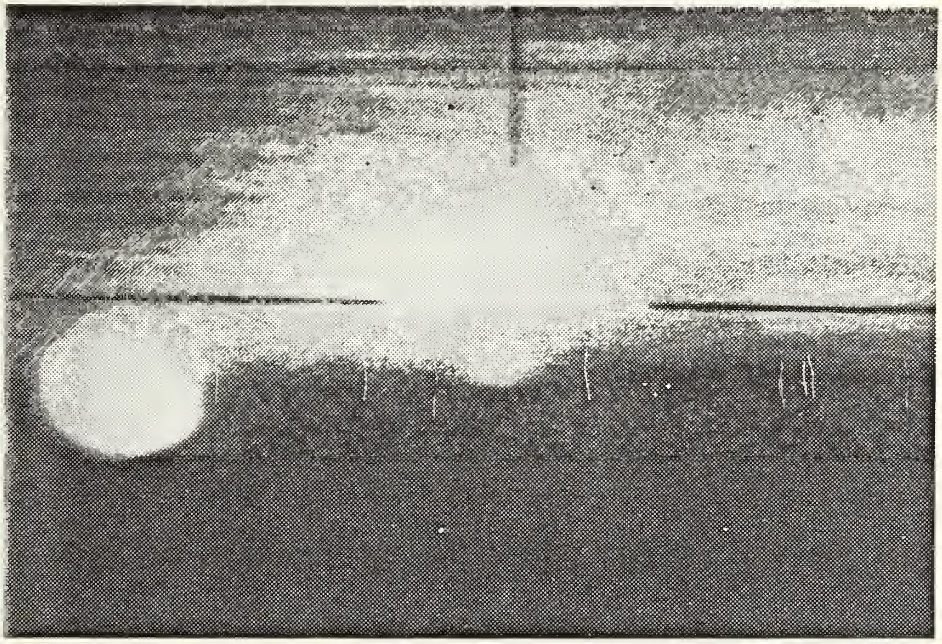


e. Fifth in Sequence of Five

Figure 4.2 Ti/2B at Low G in the Boundary Layer (Scale: 1"=3.175mm, Time Between Frames=1/3000s) (contd)

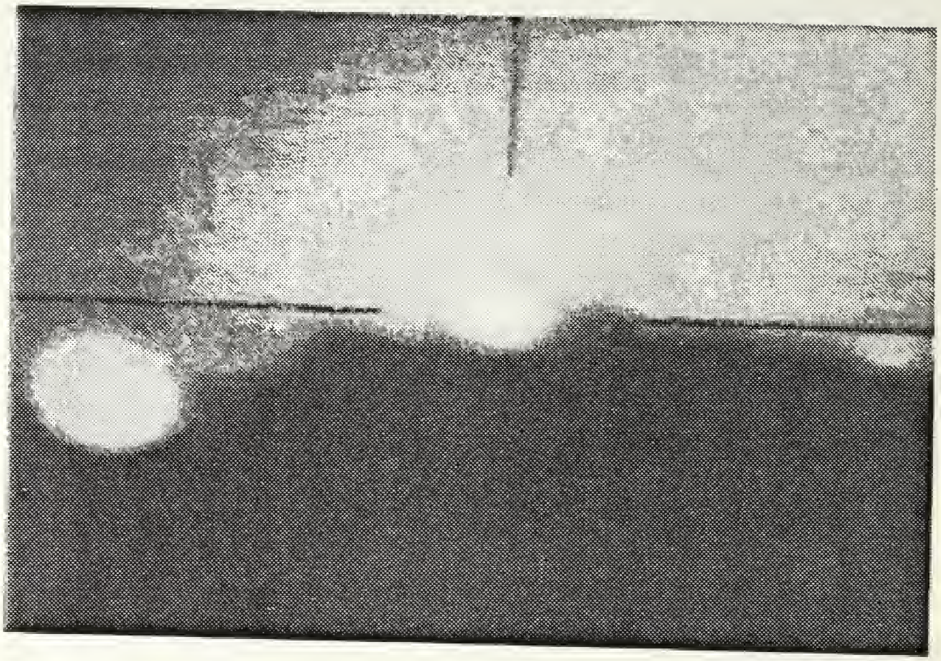
0.00013 seconds exposure. The time between frames was approximately 1/3000th of a second. Gas flow velocities based on one-dimensional flow were calculated to be approximately 200 feet per second. Velocities based on film streak length were approximately 230 feet per second. Unfortunately, the timing light oscillator which accurately puts timing marks on the film failed. As a result, film speed was estimated as a function of film length from later films in which the oscillator was functioning.

Figure 4.3 shows a sequence of multiple particle interactions. The larger particle at the left rolls past the central particles and into the core flow. Evident in

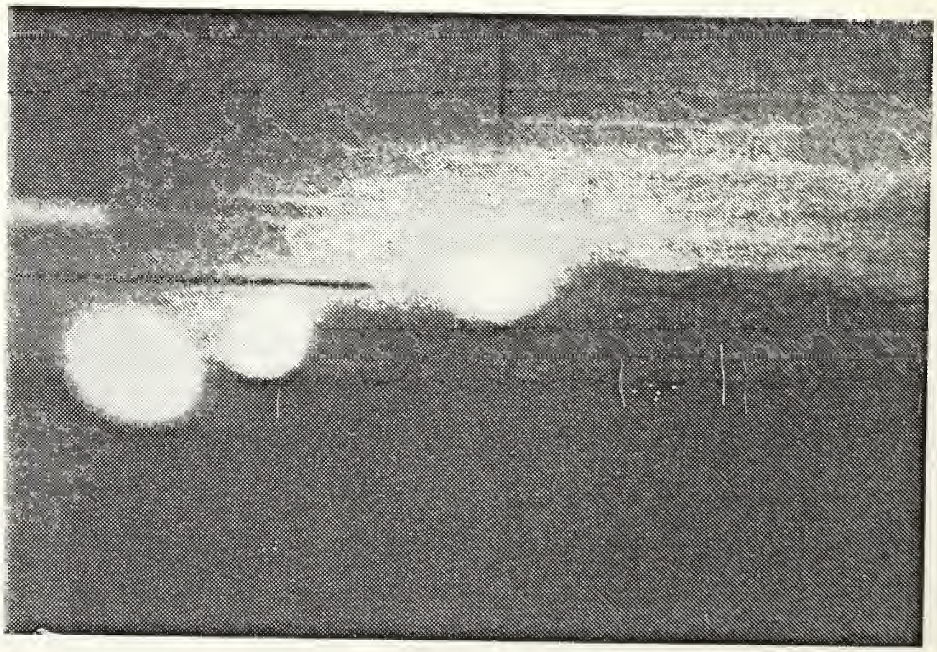


a. First in Sequence of Six

Figure 4.3 Ti/2B at Low G in the Boundary Layer (Scale: 1"=3.175mm, Time Between Frames=1/3000s)

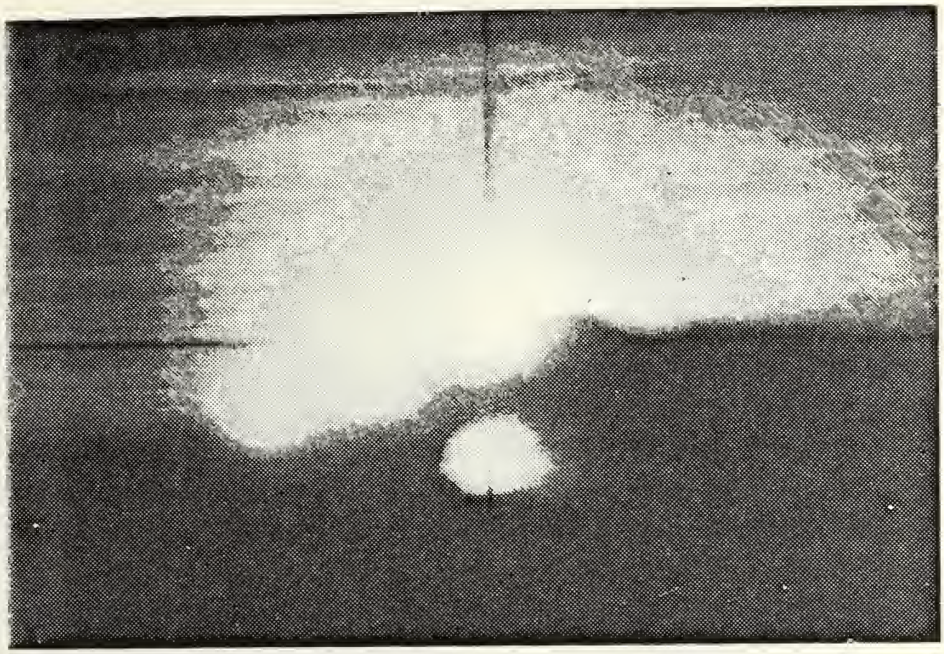


b. Second in Sequence of Six

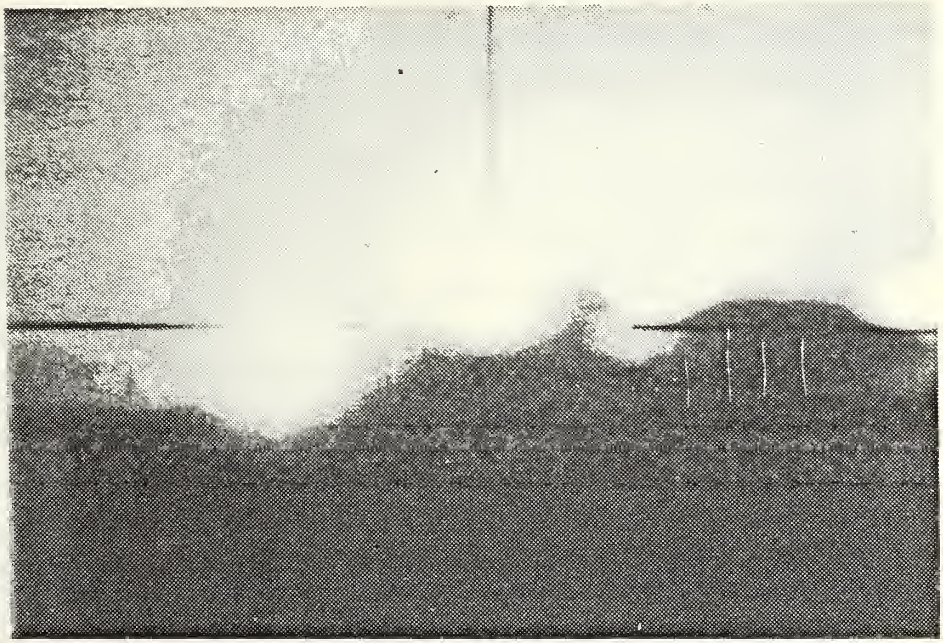


c. Third in Sequence of Six

Figure 4.3 Ti/2B at Low G in the Boundary Layer (Scale: 1"=3.175mm, Time Between Frames=1/3000s) (contd)

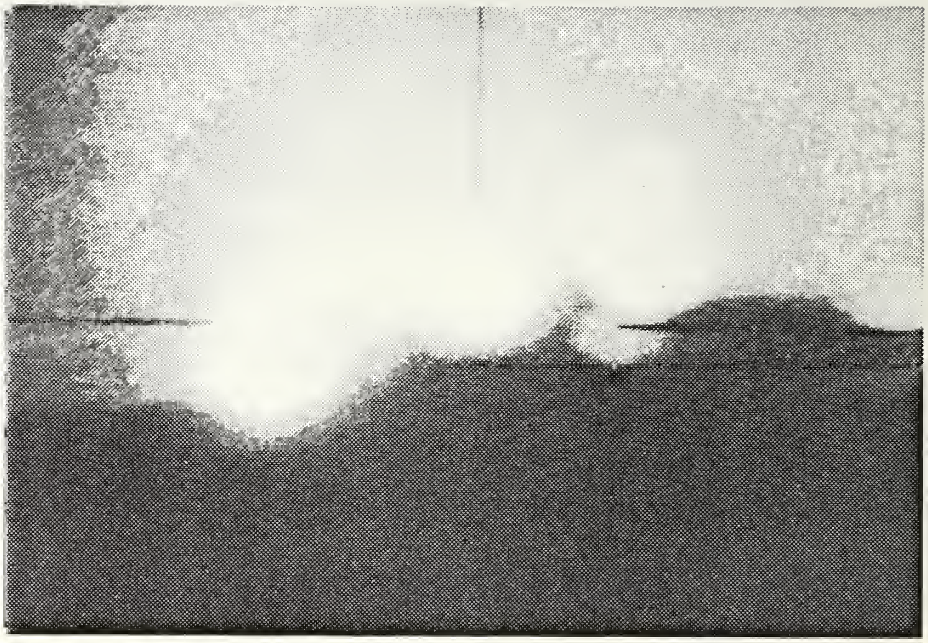


d. Fourth in Sequence of Six



e. Fifth in Sequence of Six

Figure 4.3 Ti/2B at Low G in the Boundary Layer (Scale: 1"=3.175mm, Time Between Frames=1/3000s) (contd)



f. Sixth in Sequence of Six

Figure 4.3 Ti/2B at Low G in the Boundary Layer (Scale: 1"=3.175mm, Time Between Frames=1/3000s) (contd)

the color photographs was the presence of greenish colored gases below the large particle, typical of boron combustion. It was not clear whether the flaming particle or the surface was emitting the green color.

Figure 4.4 shows a large agglomerate with the upstream edge exploding, ejecting several medium sized particles into the core flow. Once again, greenish gases were evident in the color photos.

Figure 4.5 shows the ejection of a small particle into the core flow. The ejection angle was 53 degrees and the ejection velocity was 20-25 feet per second.

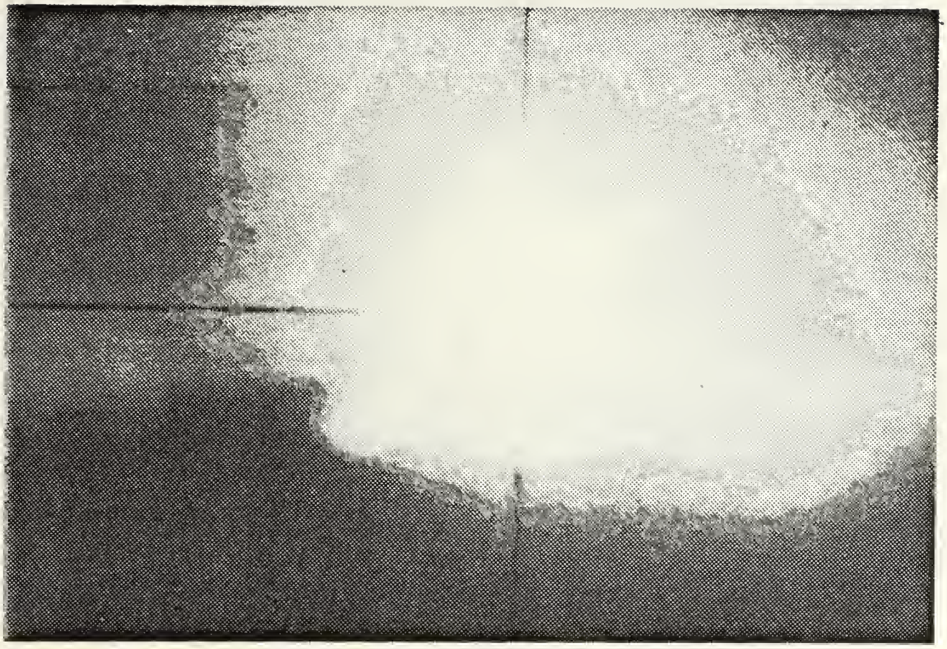
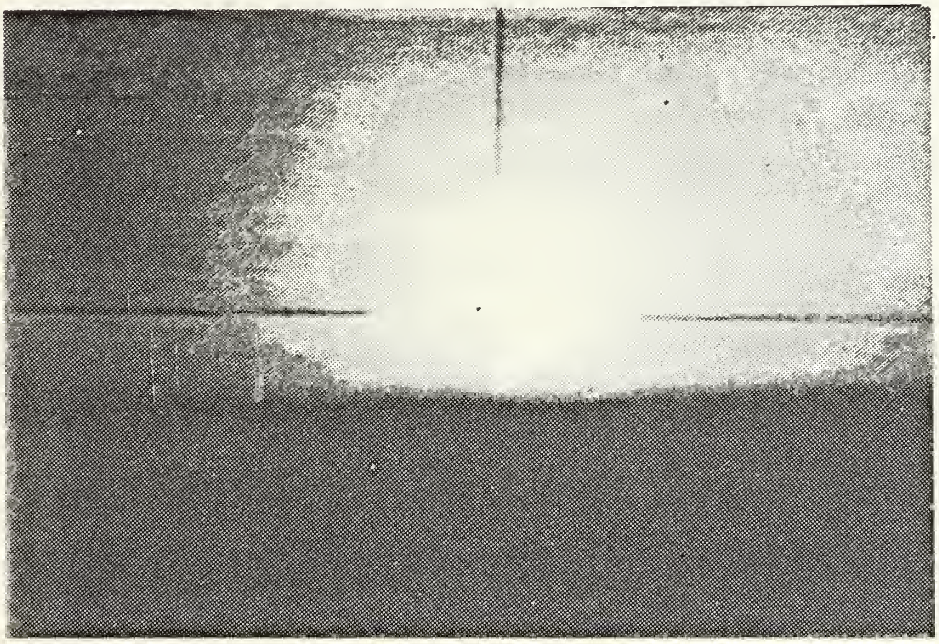
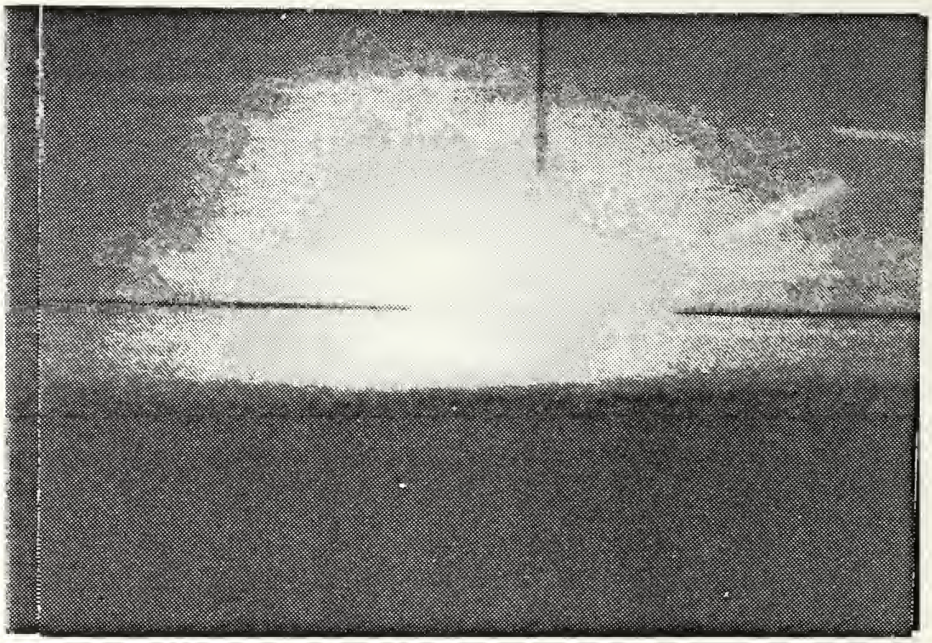


Figure 4.4 Ti/2B at Low G in the Boundary Layer (Scale: 1"=3.175mm, Time Between Frames=1/3000s)



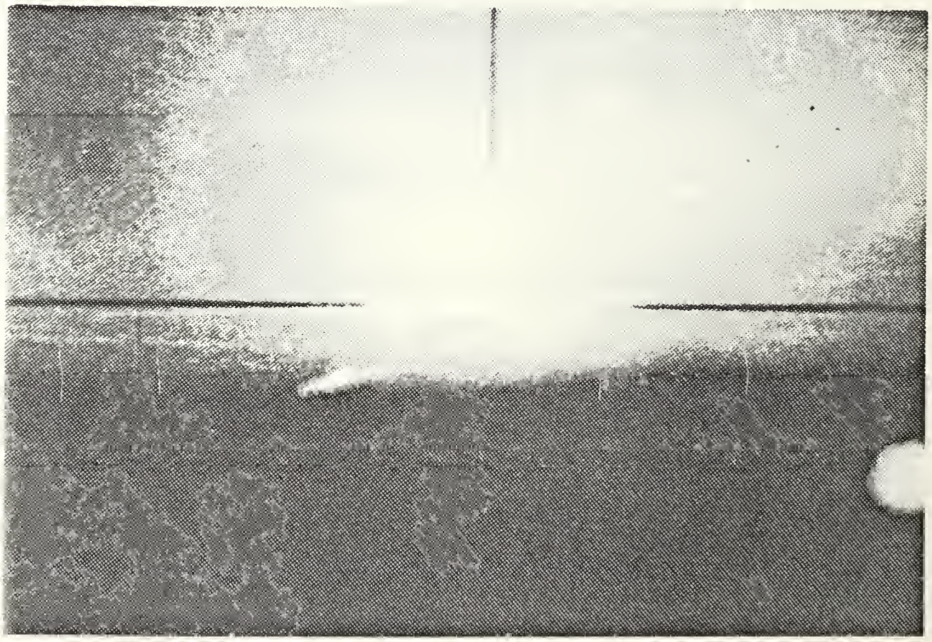
a. First in Sequence of Two

Figure 4.5 Ti/2B at Low G in the Boundary Layer (Scale: 1"=3.175mm, Time Between Frames=1/3000s)



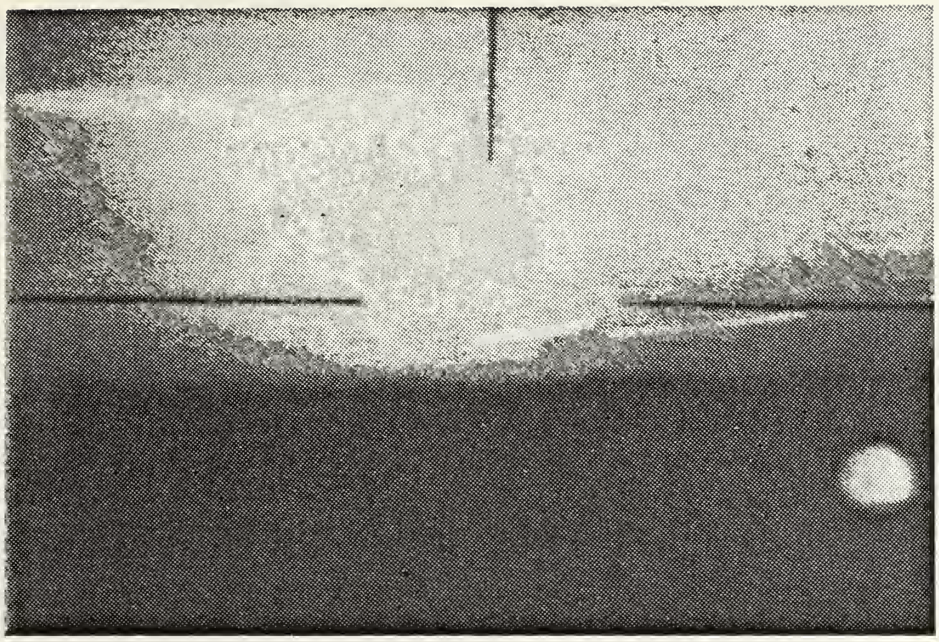
b. Second in Sequence of Two

Figure 4.5 Ti/2B at Low G in the Boundary Layer (Scale: 1"=3.175mm, Time Between Frames=1/3000s) (contd)



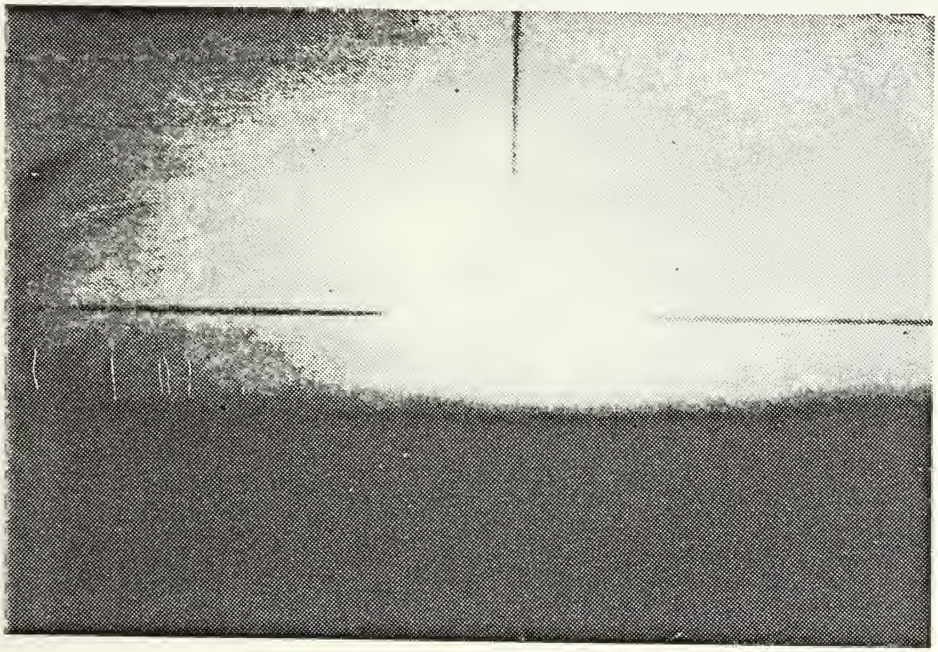
a. First in Sequence of Two

Figure 4.6 Ti/2B at Low G in the Boundary Layer (Scale: 1"=3.175mm, Time Between Frames=1/3000s)



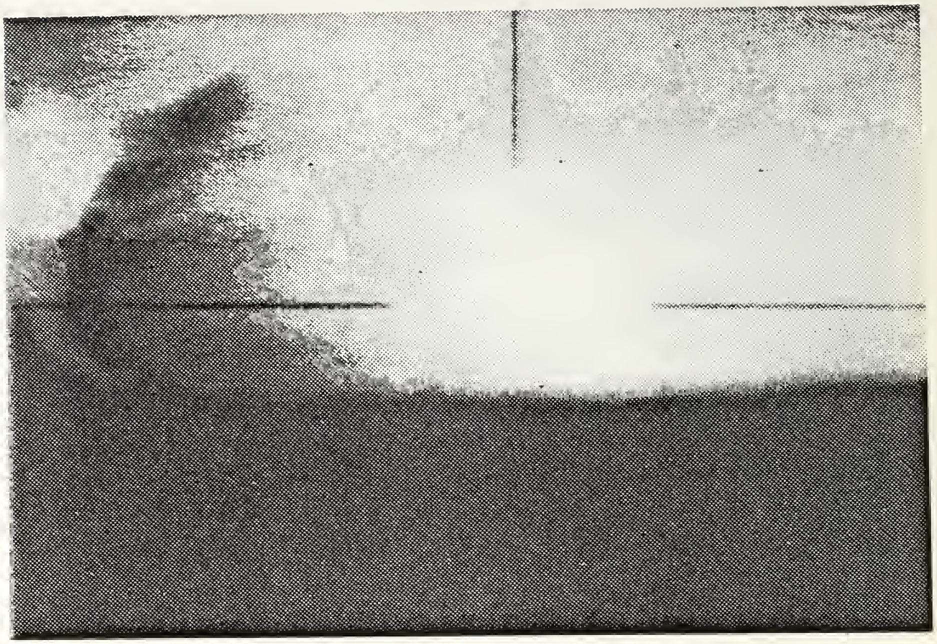
b. Second in Sequence of Two

Figure 4.6 Ti/2B at Low G in the Boundary Layer (Scale: 1"=3.175mm, Time Between Frames=1/3000s) (contd)

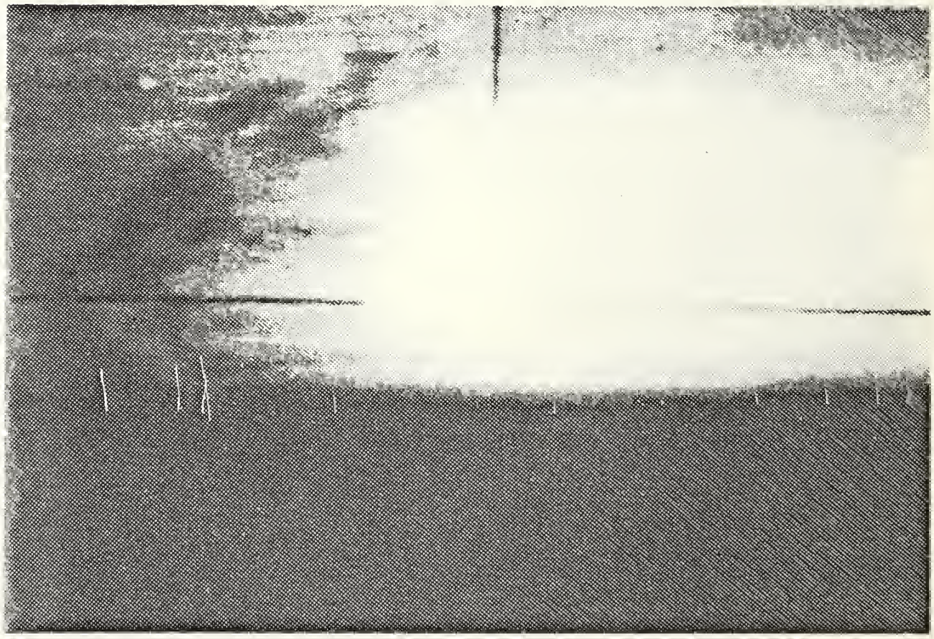


a. First in Sequence of Five

Figure 4.7 Ti/2B at Low G in the Boundary Layer (Scale: 1"=3.175mm, Time Between Frames=1/3000s)

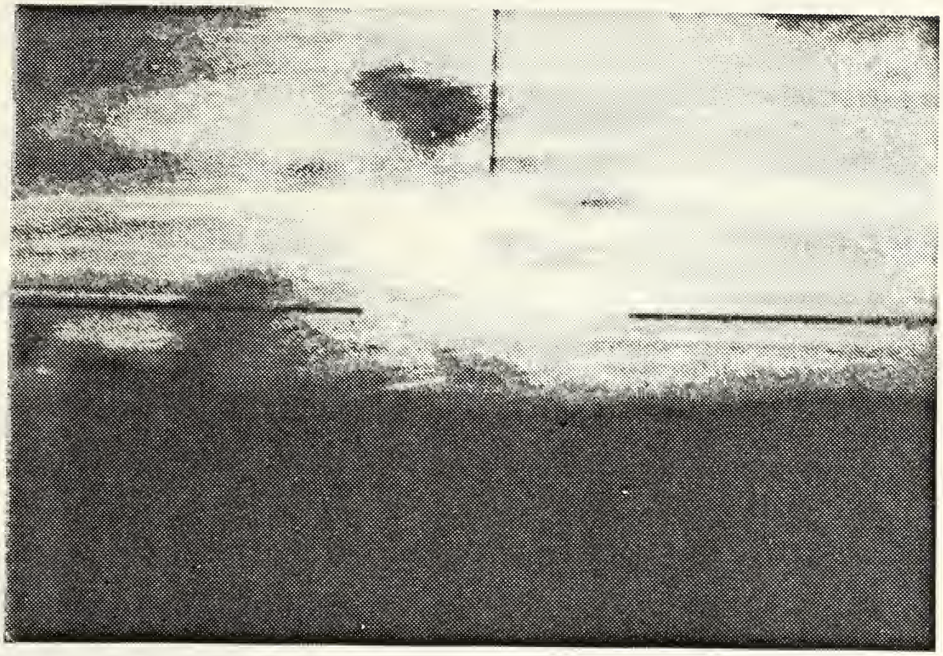


b. Second in Sequence of Five

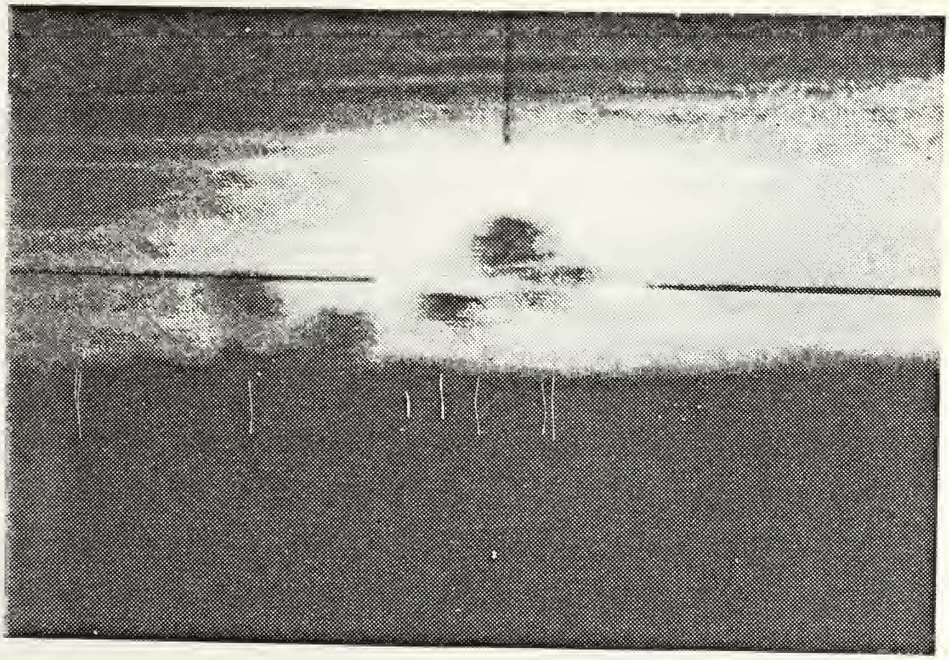


c. Third in Sequence of Five

Figure 4.7 Ti/2B at Low G in the Boundary Layer (Scale: 1"=3.175mm, Time Between Frames=1/3000s) (contd)



d. Fourth in Sequence of Five



e. Fifth in Squence of Five

Figure 4.7 Ti/2B at Low G in the Boundary Layer (Scale: 1"=3.175mm, Time Between Frames=1/3000s) (contd)

Figure 4.6 shows the ejection of two small particles at ejection angles of 15 and 20 degrees. The second photo shows the particles as they accelerate to core flow velocity.

Figure 4.7 shows a surface shedding sequence. Non-burning surface material was shed into the core flow where it broke up. The material may be non-combustible slag or surface fuel which is weakened by thermal and aerodynamic loads. It may burn in the oxygen rich core flow.

b. Ti/2B (Large Particle Sizes) at Low G in the Recirculation Zone

Large particles were seen being ejected, some partially burning. One "explosion" from deep within the fuel grain blew a large amount of material into the core flow.

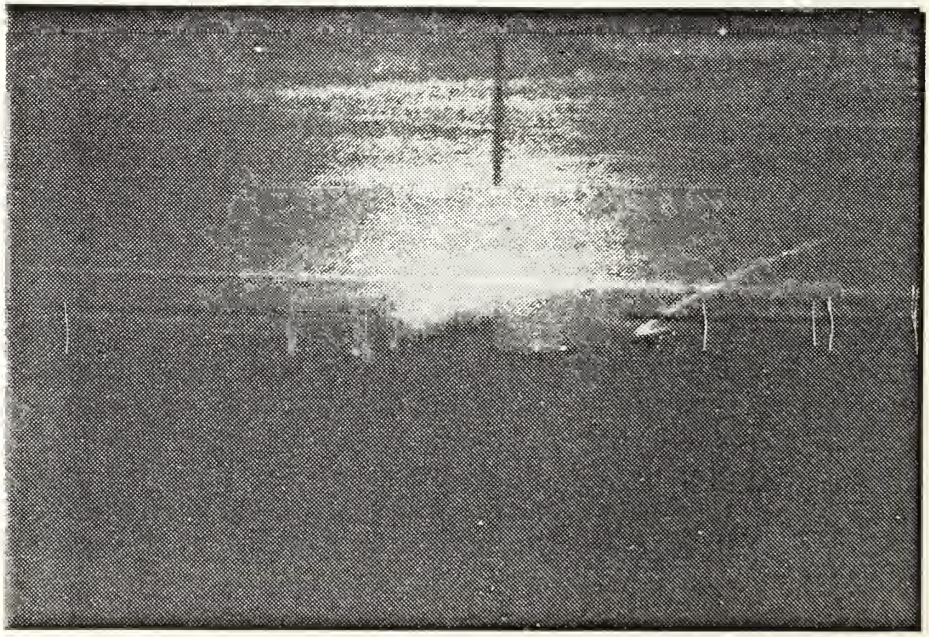


Figure 4.8 Ti/2B at High G in the Boundary Layer (Scale: 1"=3.175mm, Time Between Frames=1/3000s)

c. Ti/2B (Large Particle Sizes) at High G in the Boundary Layer Region

Figure 4.8 shows high velocity particles in the gas phase, moving at approximately 480 feet per second based on motor flow conditions. A particle is also seen being ejected at an angle of 40 degrees.

Figure 4.9 shows multiple particle ejections at low angles ranging from 3 degrees to 20 degrees.

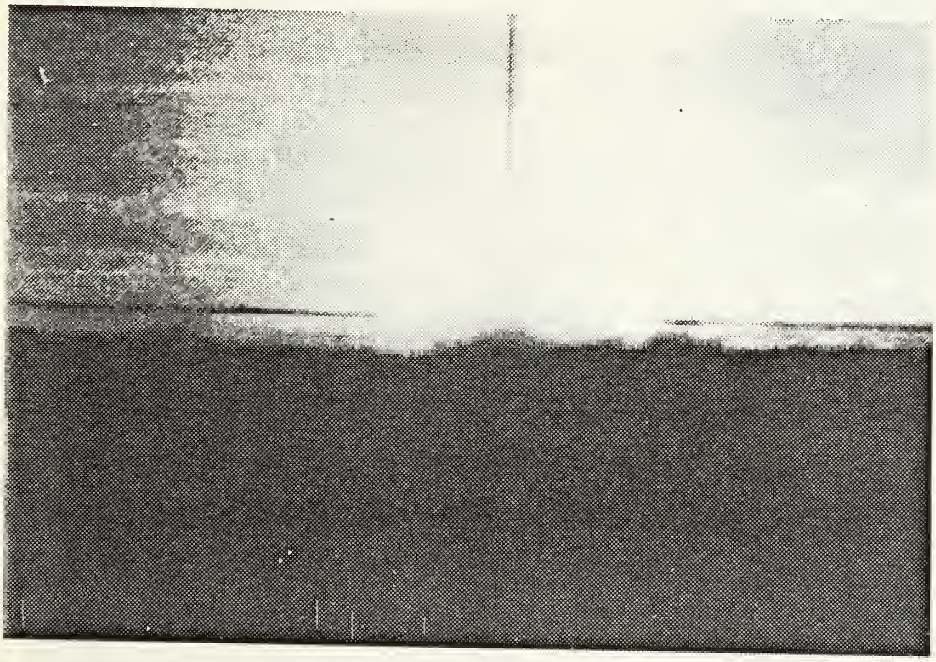


Figure 4.9 Ti/2B at High G in the Boundary Layer (Scale: 1"=3.175mm, Time Between Frames=1/3000s)

Figure 4.10 shows many high velocity, small particles with several larger particles traveling at similar velocities.

In general, high G conditions resulted in larger numbers of small particles, with only a few larger particles evident. No large agglomerates were seen on the surface and no shedding of surface material was witnessed at high G conditions, in contrast to the low G behavior.

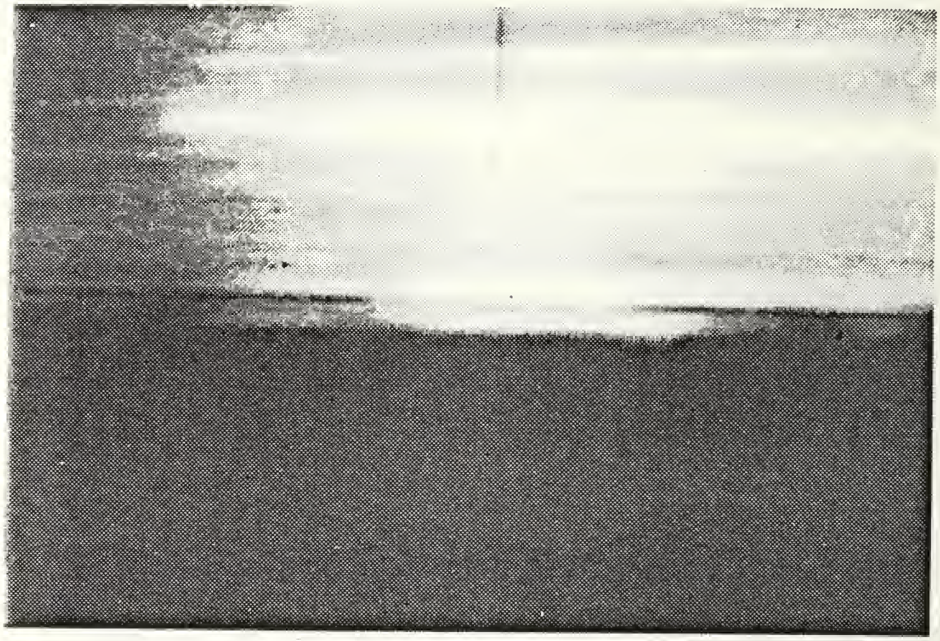


Figure 4.10 Ti/2B at High G in the Boundary Layer (Scale: 1"=3.175mm, Time Between Frames=1/3000s)

d. Ti/2B (Small Particle Sizes) at Low G in the Boundary Layer Region

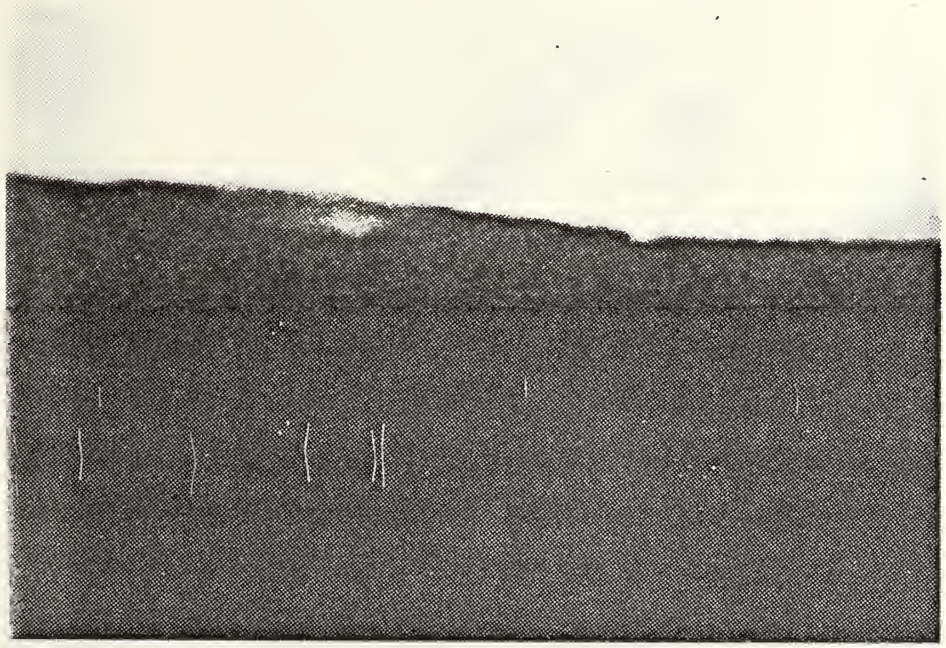
The small grain Ti/2B showed similar results to the larger grain fuel. Green flames were visible on large agglomerates burning on the surface.

e. Ti/2B (Small Particle Sizes) at Low G in the Recirculation Zone

Many small particles were seen growing larger with characteristic green "flames."

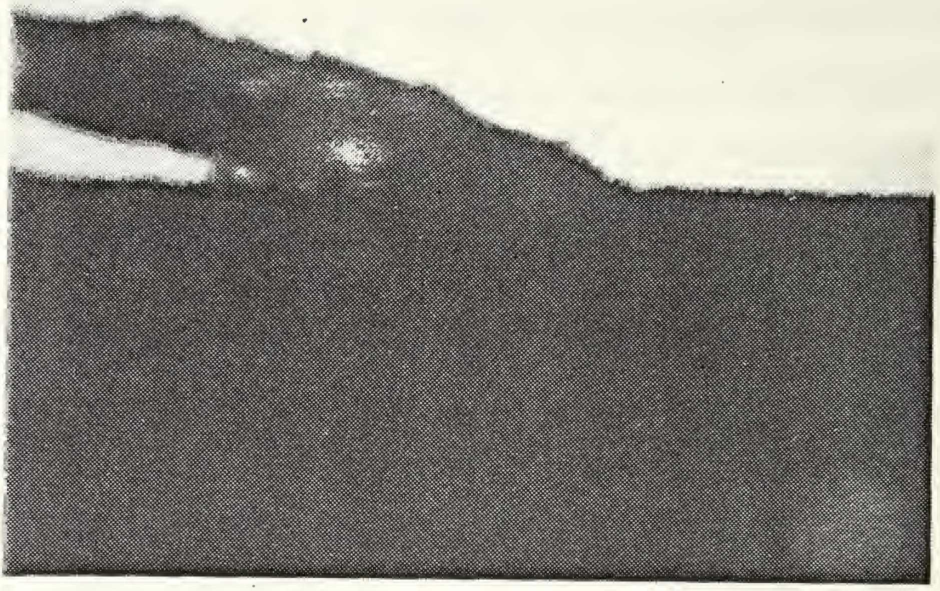
f. Ti/2B/LiF/Mg at Low G in the Boundary Layer Region

Figure 4.11 shows a very large flake of surface material coming loose from the surface and breaking up in the core flow. The flake appears to be glowing on the bottom, away from the core flow. In contrast to the Ti/2B fuels, many more large flakes were evident with this fuel.

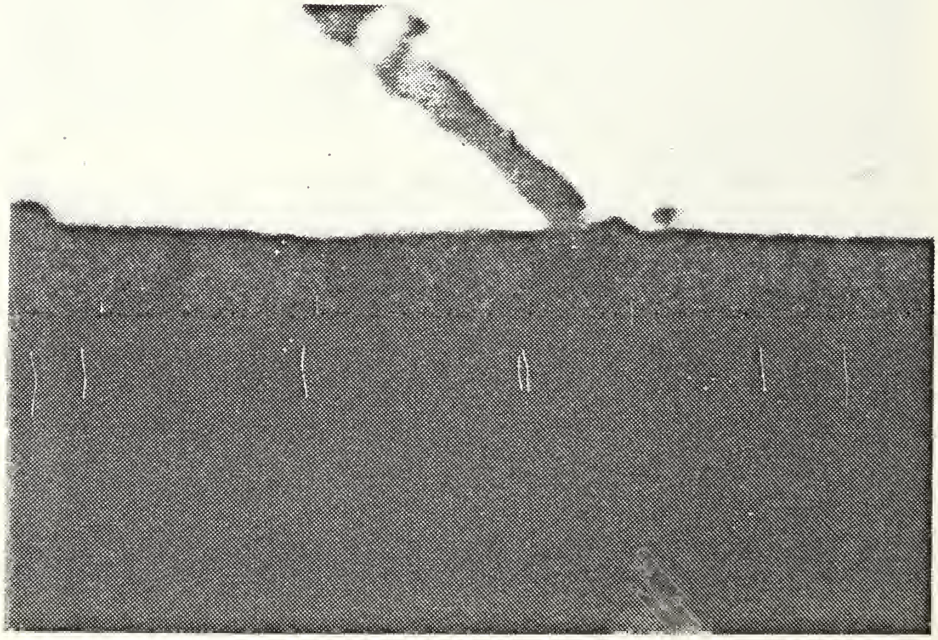


a. First in Sequence of Five

Figure 4.11 Ti/2B/LiF/Mg at Low G in the Boundary Layer (Scale: 1"=3.175mm, Time Between Frames= 1/3000s)



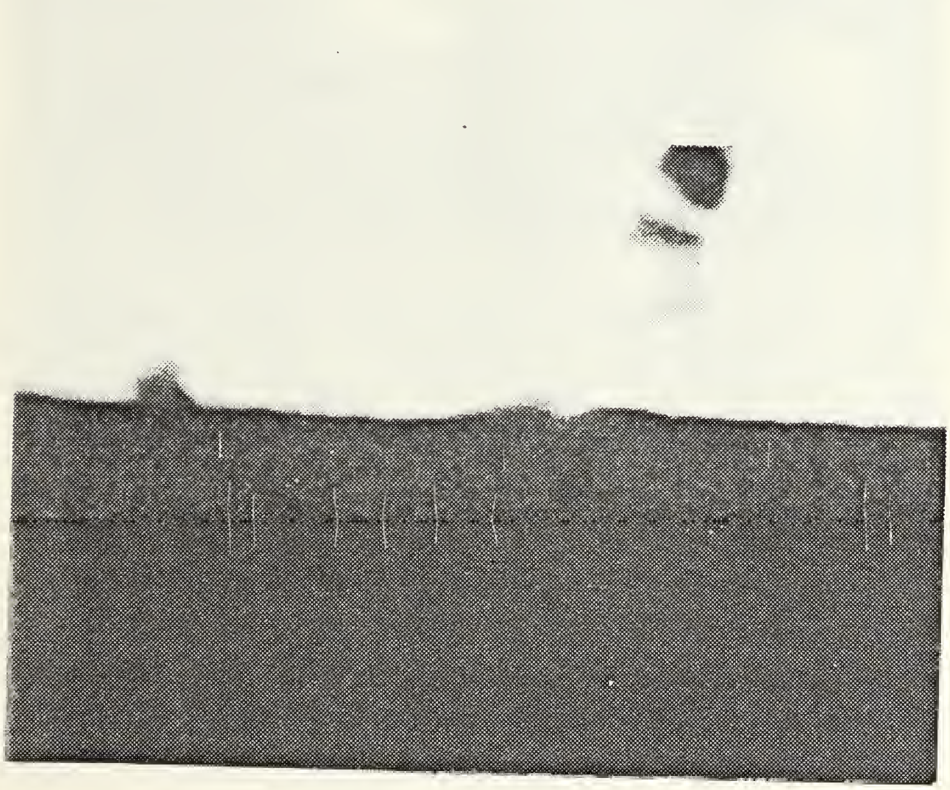
b. Second in Sequence of Five



c. Third in Sequence of Five

Figure 4.11 Ti/2B/LiF/Mg at Low G in the Boundary Layer (Scale: 1"=3.175mm, Time Between Frames= 1/3000s) (contd)

d. Fourth in Sequence of Five



e. Fifth in Sequence of Five

Figure 4.11 Ti/2B/LiF/Mg at Low G in the Boundary Layer (Scale: 1"=3.175mm, Time Between Frames= 1/3000s) (contd)

g. Ti/2B/LiF/Mg at High G in the Boundary Layer Region

In contrast to the low G film the high G film showed no surface flaking. The surface appeared moltent and glowing.

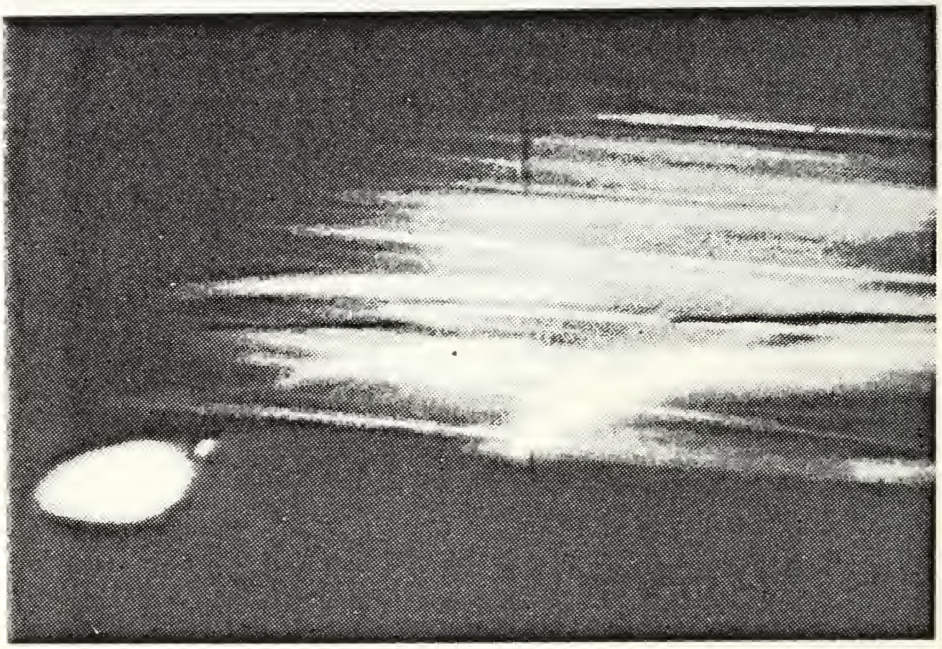


Figure 4.12 Ti/2B/AlB$_{12}$/LiF/Mg at High G in the Recirculation Zone (Scale: 1"=3.175mm, Time Between Frames=1/3000s)

h. Ti/2B/AlB$_{12}$/LiF/Mg at High G in the Recirculation Zone

Figure 4.12 shows high angle particle ejections in a down stream direction. Also, many small high velocity particles are seen.

Figure 4.13 shows several particles with ejection angles ranging from 70 to 135 degrees. The reattachment point appears to have migrated downstream, allowing upstream directed particle ejections. When viewing the film, the reattachment point appeared to oscillate back and forth in front of the window.

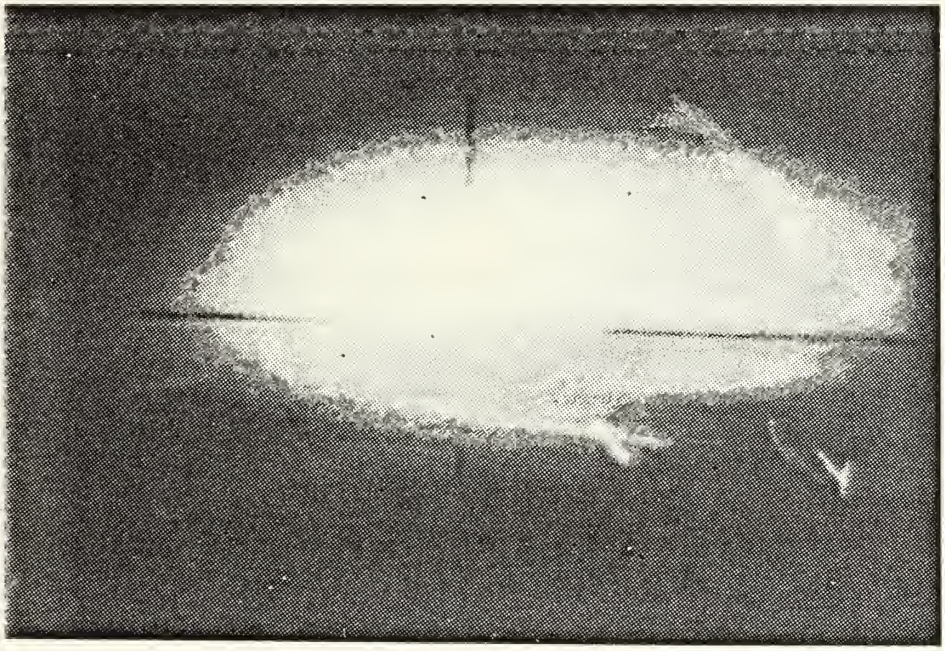


Figure 4.13 Ti/2B/AlB_{12}/LiF/Mg at High G in the Recirculation Zone (Scale: 1"=3.175mm, Time Between Frames=1/3000s)

V. CONCLUSIONS AND RECOMMENDATIONS

Each metallized fuel burned slightly different. These differences in burning characteristics were difficult to predict a-priori. Filming combustion events inside the two-dimensional motor requires precise light control. F-stop settings were based on previous experience. Some films were of little value due to under and over-exposure. Low pressure f-stop settings were used for higher pressure runs. The fuels in general burned better, and therefore brighter, at the higher pressures. As a result, all but one of the films shot at high pressure were over-exposed. In the future, when shooting at high pressure conditions, the f-stop setting should be increased from f=5.6 to f=8 or 11. Possibly some way of metering the light can be developed to prevent the waste of film and fuel.

There was evidence that both minor binder ingredient changes (polymer and curative) and the inclusion of magnesium resulted in larger required inlet step heights to sustain combustion. Most of the metallized fuels did not burn well at pressures below approximately 40 psia. Low air mass fluxes generally resulted in larger metallic surface agglomerations, larger particles in the gas phase and more dominate shedding of surface layers.

APPENDIX A

TABLE A1

SUMMARY OF MOTOR TEST CONDITIONS

TEST NUMBER	FUEL TYPE	SHORE HARD-NESS	TEST DATE	MOTOR CONDITIONS							CAMERA A RECIRCULATION ZONE	CAMERA C BOUNDARY LAYER ZONE
				NOZZLE THROAT DIA (IN)	PORT HEIGHT (IN)	INLET HEIGHT (IN)	G $(\frac{\text{lbm}}{\text{S}\cdot\text{IN}^2})$	$\dot{M}_a$ $(\frac{\text{lbm}}{\text{S}})$	P_c psia	T_a (°R)		
33	CSD- 717- 722 Ti/2B	20	22 JAN	1.5	1.0	0.5	0.5	1.299	60		5000 pps New Lens Angled down 2 degrees	5000 pps f=5.6 Angled down 2 degrees
34	CSD- 717- 722 Ti/2B	20	24 JAN	1.125	1.0	0.5	0.2	0.503	55	1250	5000 pps New Lens Angled down 2 degrees	5000 pps f=5.6 Angled down 2 degrees
39	CSD- 746 Ti/2B	26	5 FEB	1.5	1.0	0.5	0.5	1.245	59	1167	5000 pps New Lens Angled down 2 degrees	5000 pps f=5.6 Angled down 2 degrees
40	CSD- 746 Ti/2B	26	6 FEB	1.125	1.0	0.5	0.2	.536	70	1175	5000 pps New Lens Angled down 2 degrees	5000 pps f=5.6 Angled down 2 degrees
47	CSD- 746 Ti/2B	26	25	.95	1.0	0.5	0.5	1.29	200	1072	6000 pps New Lens Angled down 2 degrees	6000 pps f=5.6 Angled down 2 degrees

TABLE A1 (contd)

SUMMARY OF MOTOR TEST CONDITIONS

TEST NUMBER	FUEL TYPE	SHORE HARD-NESS	TEST DATE	MOTOR CONDITIONS							CAMERA A RECIRCULATION ZONE	CAMERA C BOUNDARY LAYER ZONE
				NOZZLE THROAT DIA (IN)	PORT HEIGHT (IN)	INLET HEIGHT (IN)	G $(\frac{\text{lbm}}{\text{S}\cdot\text{IN}^2})$	$\dot{M}_a$ $(\frac{\text{lbm}}{\text{S}})$	P_c psia	T_a (°R)		
35	CSD-744 Ti/2B LiF Mg	45	27 JAN	1.125	1.0	0.5	0.2	0.489	50	1200	5000 pps New Lens Angled down 2 degrees	5000 pps f=5.6 Angled down 2 degrees
36	CSD-744 Ti/2B LiF Mg	45	28 JAN	.95	1.0	0.5	0.2	0.523	72	1060	No Film	5000 pps f=5.6 Angled down 2 degrees
37	CSD-744 Ti/2B LiF Mg	45	29 JAN	1.35	1.0	0.5	0.479	1.198	91	1069	5000 pps New Lens Angled down 2 degrees	5000 pps f=5.6 Angled down 2 degrees
41	CSD-747 Ti/2B AlB_{12} LiF Mg	58	6 FEB	1.125	1.0	0.5	0.2	0.526	39	1217	5000 pps New Lens Angled down 2 degrees	5000 pps f=5.6 Angled down 2 degrees
42	CSD-747 Ti/2B AlB_{12} LiF Mg	58	7 FEB	1.5	1.0	0.5	0.5	1.25	50	1082	5000 pps New Lens Angled down 2 degrees	5000 pps f=5.6 Angled down 2 degrees

TABLE A1 (contd)

SUMMARY OF MOTOR TEST CONDITIONS

TEST NUMBER	FUEL TYPE	SHORE HARD-NESS	TEST DATE	MOTOR CONDITIONS							CAMERA A RECIRCULATION ZONE	CAMERA C BOUNDARY LAYER ZONE
				NOZZLE THROAT DIA (IN)	PORT HEIGHT (IN)	INLET HEIGHT (IN)	G $(\frac{lbm}{S \cdot IN^2})$	$\dot{M}_a$ $(\frac{lbm}{S})$	P_c psia	T_a (°R)		
43	CSD-747 Ti/2B AlB_{12} LiF Mg	58	8 FEB	1.35	1.0	0.5	0.48	1.19	72	1172	6000 pps f=3.5 Angled down 8 degrees	6000 pps New Lens Angled down 8 degrees
44	CSD-749 Ti/2B Teflon	55	21 FEB	1.5	1.0	0.5	0.52	1.31	40	1050	6000 pps New Lens Angled down 2 degrees	6000 pps f=5.6 Angled down 2 degrees
45	CSD-749 Ti/2B Teflon	55	21 FEB	1.35	1.0	0.5	0.5	1.235	49	1214	No Film	No Film
45B	CSD-749 Ti/2B Teflon	55	24 FEB	1.35	1.0	0.5	0.54	1.34	53	1060	6000 pps New Lens Angled down 2 degrees	6000 pps f=5.6 Angled down 2 degrees
46	CSD-749 Ti/2B Teflon	55	24 FEB	.95	1.0	0.5	0.53	1.34	180	1064	6000 pps New Lens Angled down 2 degrees	6000 pps f=5.6 Angled down 2 degrees

TABLE A1 (contd)

SUMMARY OF MOTOR TEST CONDITIONS

TEST NUMBER	FUEL TYPE	SHORE HARD-NESS	TEST DATE	MOTOR CONDITIONS							CAMERA A RECIRCULATION ZONE	CAMERA C BOUNDARY LAYER ZONE
				NOZZLE THROAT DIA (IN)	PORT HEIGHT (IN)	INLET HEIGHT (IN)	G $(\frac{lbm}{S \cdot IN^2})$	$\dot{M}_a$ $(\frac{lbm}{S})$	P_c psia	T_a (°R)		
50	ARC-1 B Mg	62	26 FEB	1.5	1.0	0.5	0.5	1.266	76	1123	No Film	No Film
51	ARC-1 B Mg	62	26 FEB	.95	1.0	0.5	0.5	1.266	193	1126	6000 pps New Lens Angled down 2 degrees	6000 pps f=5.6 Angled down 2 degrees
52	ARC-1 B Mg	62	26 FEB	1.35	1.0	0.5	0.5	1.22	85	1140	6000 pps New Lens Angled down 2 degrees	6000 pps f=5.6 Angled down 2 degrees
55	ARC-1 B Mg	62	26 FEB	1.5	1.0	0.5	0.5	1.23	52	130	No Film	6000 pps f=5.6 Angled down 2 degrees
56	ARC-1 B Mg	62	27 FEB	1.35	1.0	0.5	0.5	1.267	55	1109	No Film	No Film

TABLE A1 (contd)

SUMMARY OF MOTOR TEST CONDITIONS

TEST NUMBER	FUEL TYPE	SHORE HARD-NESS	TEST DATE	MOTOR CONDITIONS							CAMERA A RECIRCULATION ZONE	CAMERA C BOUNDARY LAYER ZONE
				NOZZLE THROAT DIA (IN)	PORT HEIGHT (IN)	INLET HEIGHT (IN)	G $(\frac{lbm}{S\cdot IN^2})$	$\dot{M}_a$ $(\frac{lbm}{S})$	P_c psia	T_a (°R)		
53	ARC-2 B Teflon	70	26 FEB	.95	1.0	0.5	0.5	1.242	175.6	1142	6000 pps New Lens Angled down 2 degrees	6000 pps f=5.6 Angled down 2 degrees
54	ARC-2 B Teflon	70	26 FEB	1.5	1.0	0.5	0.47	1.186	51	1220	6000 pps New Lens Angled down 2 degrees	6000 pps f=5.6 Angled down 2 degrees
38	NWC- equal parts Boron Carbide Mg	72	30 JAN	1.35	1.0	0.5	0.5	1.253	75	1080	No Film	5000 pps f=5.6 Angled down 2 degrees
57	NWC- equal parts Boron Carbide Mg	72	3 MAR	1.35	1.0	0.5	0.5	1.24			No Film	No Film
58	NWC- equal parts Boron Carbide Mg	72	3 MAR	1.35	1.0	0.35	0.2	0.515	36	1009	6000 pps New Lens Angled down 2 degrees	6000 pps f=5.6 Angled down 2 degrees

TABLE A1 (contd)

SUMMARY OF MOTOR TEST CONDITIONS

TEST NUMBER	FUEL TYPE	SHORE HARD-NESS	TEST DATE	MOTOR CONDITIONS							CAMERA A RECIRCULATION ZONE	CAMERA C BOUNDARY LAYER ZONE
				NOZZLE THROAT DIA (IN)	PORT HEIGHT (IN)	INLET HEIGHT (IN)	G $(\frac{lbm}{S \cdot IN^2})$	$\dot{M}_a$ $(\frac{lbm}{S})$	P_c psia	T_a (°R)		
59	NWC +5% B_4C -5% Mg	75	3 MAR	1.35	1.0	0.35	0.5				6000 pps New Lens Angled down 2 degrees	6000 pps f=5.6 Angled down 2 degrees
48	NWC +20% B_4C -15% Mg	74	25 FEB	.95	1.0	0.5	0.52	1.30	200	1130	No Film	No Film

TABLE A2

SUMMARY OF OBSERVATIONS

TEST NUMBER	FUEL TYPE	COMMENTS AND INITIAL OBSERVATIONS	COMMENTS ON FILMS WINDOW A = RECIRCULATION ZONE WINDOW C = BOUNDARY LAYER ZONE
33	CSD-7170 722 Ti/2B	Good Ignition Good Burn Front Window Burned Aft Window OK Fuel Burned Well Level Across Grain	A - Many glowing particles, no surface shots. C - Small ejection events in almost every frame. Small non-burning particles roll on surface.
34	CSD-717- 722 Ti/2B	Long Time for Ignition Good Burn Windows OK	A - White hot particles seen leaving surface. One explosion from deep within blows partly burning particles into gas flow. C - Large glowing particle rolls off surface and is contrasted with a particle in the gas glow.
39	CSD-746 Ti/2B	Good Ignition Good Burn Windows Burned Fuel Burned Well in Front of Windows	A - Nothing C - Nothing
40	CSD-746 Ti/2B	Good Ignition Good Burn Windows Good	A - Small particles growing larger with flames, very good. C - Explodes from within blowing out white hot particles, many glowing particles.
47	CSD-746 Ti/2B	Good Burn Windows OK Lots of Surface Slag When Fuel Removed	A - Film over exposed; some surface shots, mostly white hot particles. C - Over exposed, many white hot particles.

TABLE A2 (contd)

SUMMARY OF OBSERVATIONS

TEST NUMBER	FUEL TYPE	COMMENTS AND INITIAL OBSERVATIONS	COMMENTS ON FILMS WINDOW A = RECIRCULATION ZONE WINDOW C = BOUNDARY LAYER ZONE
35	CSD-744 Ti/2B LiF Mg	Long Time for Ignition Poor Burn Front Window Burned Aft Window OK Fuel Did Not Burn Well in Front of Windows	A - Some flaking flakes build a slag layer toward the flame and burn cherry red away from the flame. Many glowing particles. C - Cold surface events. Fuel appears sticky.
36	CSD-744 Ti/2B LiF Mg	Good Ignition Good Burn Aft Window Good Fuel Burned Better in Center of Motor	C - Many large flakes, appear to be burning on fuel side but not on fire side, many small burning particles in background.
37	CSD-744 Ti/2B LiF Mg	Poor Ignition OK Burn Back Window Fogged Front Window Burned	A - Nothing C - Surface glowing red hot with flames coming off, not many ejections.
41	CSD-747 Ti/2B AlB_{12} LiF Mg	Good Ignition Poor Burn Film Shot as Engine Died Windows Good	A - Nothing C - Nothing
42	CSD-747 Ti/2B AlB_{12} LiF Mg	Good Ignition No Burn Picture Shot with Ignition on Aft Window Fowled Front Window OK	A - Nothing C - Nothing

TABLE A2 (contd)

SUMMARY OF OBSERVATIONS

TEST NUMBER	FUEL TYPE	COMMENTS AND INITIAL OBSERVATIONS	COMMENTS ON FILMS WINDOW A = RECIRCULATION ZONE WINDOW C = BOUNDARY LAYER ZONE
43	CSD-747 Ti/2B AlB_{12} LiF Mg	Good Ignition Good Burn Front Windows OK Aft Window Fowled Fuel Potted Looks Like Moon Scape	A - Small energetic particals hitting surface, medium sized particles glowing and leaving surface. Some particle ejections. C - Over exposed.
44	CSD-749 Ti/2B Teflon	Engine Died - Film Shot with Engine Dying Windows Good	A - Nothing C - Nothing
45	CSD-749 Ti/2B Teflon	No Burn O_2 Valve Failed	No Films
45B	CSD-749 Ti/2B Teflon	Good Burn Not Many Sparks	A - Nothing, under exposed. C - Nothing, film must have been shot after engine died.
46	CSD-749 Ti/2B Teflon	Great Burn Very Bright Front Window Fowled	A - Over exposed, many white hot particles some leaving the surface. C - Over exposed, nothing.
50	ARC-1 B Mg	No Sustained Burn	No Film

TABLE A2 (contd)

SUMMARY OF OBSERVATIONS

TEST NUMBER	FUEL TYPE	COMMENTS AND INITIAL OBSERVATIONS	COMMENTS ON FILMS WINDOW A = RECIRCULATION ZONE WINDOW C = BOUNDARY LAYER ZONE
51	ARC-1 B Mg	Good Burn Front Window Fowled Aft Window OK	A - Over exposed, some surface shots, many white hot particles. C - Over exposed, some surface shots many particles.
52	ARC-1 B Mg	No Sustained Burn Film Shot with Motor Out	A - Nothing C - Nothing
5	ARC-1 B Mg	Would not sustain with Zeekarez on bottom too. Front camera did not run.	C - Nothing
56	ARC-1 B Mg	No Sustained Burn O_2 Ignitor Line Failed	No Film
53	ARC-2 B Teflon	Good Burn Good Windows	A - Great surface shots, many particles leaving surface. C - A little over exposed, lots of surface flame, some slag coming off.

TABLE A2 (contd)

SUMMARY OF OBSERVATIONS

TEST NUMBER	FUEL TYPE	COMMENTS AND INITIAL OBSERVATIONS	COMMENTS ON FILMS WINDOW A = RECIRCULATION ZONE WINDOW C = BOUNDARY LAYER ZONE
54	ARC-2 B Teflon	Good Burn Good Windows	A - Nothing C - Nothing
38	NWC equal parts Boron Carbide Mg	OK Ignition Would not Sustain Burn Back Window Burned	C - Nothing
57	NWC equal parts Boron Carbide Mg	No Sustained Burn with Zecorez	No Film
58	NWC equal parts Boron Carbide Mg	Burned with increased step even with the improper nozzle (too big). Pressure too low. Windows OK	
59	NWC- +5% B_4C -5% B_4C	Good Burn Front Window Burned Aft Window OK Printer Failed Fuel Failed after Camera Shot	

TABLE A2 (contd)

SUMMARY OF OBSERVATIONS

TEST NUMBER	FUEL TYPE	COMMENTS AND INITIAL OBSERVATIONS	COMMENTS ON FILMS WINDOW A = RECIRCULATION ZONE WINDOW C = BOUNDARY LAYER ZONE
48	NWC +20% B_4C -15% Mg	No Sustained Burn	No Films

LIST OF REFERENCES

L. Alon Gany and David W. Netzer, "Combustion Studies for Solid Fuel Ramjets," AIAA paper #85-1177, 21st Joint Propulsion Conference, July 8-10, 1985, Monterey, California.

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